

Simplified Digital Lead/Lag Control Circuit Design Options

The basic objective is to simplify the current six (6) Op-amp design we used in the Spring '10 EE470 course (2 level shifters, 2 integrator for the plant, 1 gain stage, $V_{ref} = -2.5v$). My goal is to simplify both the hardware and the software. The software solution is the same for all hardware solutions. I believe the hardware problem can be attacked from multiple fronts corresponding to a series of hardware design points.

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Recommendations

Right now, my recommendation would be to build a circuit board which supports SOIC and DIP components as described in Design Point 1A. These kits would then be sold to the students. This would allow the students to solder their own boards. If a custom PCB is not available then I would go with Design Point 2. Design Point 2 is a short term solution that is simple but requires some expensive components (Arduino Mega, 28-pin DIP ADC and DACs).

Software

The timer interrupt code would be limited to something like this.

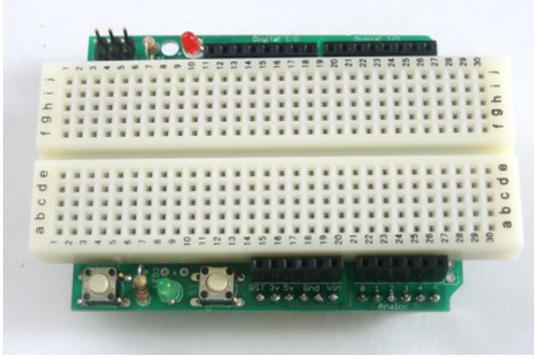
```
void sample() {
    R = setpoint()          // generate set point clock
    dn_in = readADC();     // read bipolar ADC
    E1 = R - dn_in;        // summing junction
    // lead-compensation difference equation
    U1 = A*U0 + B*E1 + C*E0;
    // update variables for next iteration
    U0 = U1;               // save current output as previous output
    E0 = E1;               // save current error as previous error
    writeDAC(U1);         // write to bipolar DAC
}
```

Much of the software complexity would be hidden in an INCLUDE file containing `readADC` and `writeADC`.

Hardware

Basic Requirements

- 12-bit resolution
- Serial Interface (I2C and/or SPI)
- 8-pin DIP
- Everything can fit on a [Sparkfun](#) or [Adafruit](#) Protoshield.



Design Point 1A - Unipolar ATmega ADC and DAC 5v Solution

This is a design variation of the EE470 circuit. The S'10 reference design is modified as follows...

- MCP1525/1541 voltage reference eliminates an op-amp buffer and voltage divider.
- Level Shifting Op-amps would use resistor values providing $\times 4$ gain and $\times \frac{1}{4}$ attenuation. This would present the plant with a uniform ± 10 v SISO solution, while only requiring a dual Op-amp IC keeping part count down.
- 8-pin DIP or 8-lead SOIC - 12-bit MCP4921 DAC (S'10 design) with serial interface with an output that swings between 0 to 5v with a single 5 v supply voltage.
- We would use the on-board ADC on the Arduino MCU, but the input to the $\times \frac{1}{4}$ level shifter would include clamping diodes and a current-limiting resistor to protect the Arduino from voltages $> +5V$ and $< 0V$.

The PCB design begins with a custom Analog Shield based on the Sparkfun Protoshield. This dual-sided PCB would have the DAC and ADC interface logic mounted on one side of the board, with a mini breadboard attached to the other. The Sparkfun Protoshield is illustrated in the Figure below which shows a nifty extension with 6-pins which in our design would provide for the analog input and output headers. The side with the breadboard would also have a socket allowing the DC/DC converter to be plugged in or provide easy access for jumper wires if the students wants to use lab supplies (*not recommended*).

The circuit board would be made for the students to purchase in a kit form. The students would then wire their "plants"/integrators to their prototyping boards and jump over to the ADC/DAC header pins as needed.

The cost of the ADC interface components, DAC, and DC-to-DC converter for this solution is less than \$15.00.



- TDK CC1R5-0512DF-E DC/DC Converters 5v to +/- 12v. [Digi-key](#) has them in stock at \$9.85.
- MCP1525/1541 2.5V/4.096V Reference Supply, this is a TO-92 three-terminal device that provide a steady +2.5V or +4.095V voltage reference. This eliminates the op-amp buffer, voltage divider, and associated discrete components. Available from [Digikey](#) with over 4,000 in stock for \$0.92.
- Custom PCB Supports the following DAC Options
 - 8-pin DIP or 8-lead SOIC - 12-bit MCP4921 DAC with serial interface packaged in with an output that swings between 0 to 5v with a single 5 v supply voltage. [Digikey](#) has over 11,000 of the [MCP4921-E/SN-ND](#) SOIC in stock and over 3,000 of the [MCP4921-E/P-ND](#) DIP in stock, both cost \$2.36.
 - TBD Op-amp provides level shifting/x4 gain stage with associated discrete components.
- ATmega328P 12-bit ADC
 - TBD Op-amp provides level shifting/x0.25 gain stage with associated discrete components.

Pluses

- Lowest cost of all the solutions.
- Custom PCB means we control the design leading to a good ground and power plane, and no wiring errors for this part of the design.
- Allows the use of Surface Mounted or Through-hole parts.
- Simplified version of Spring '10 EE470 design
- Software is done written - read/write code needs to be moved to an INCLUDE file.

Minuses

- Requires custom PCB
- Difficult to teach hardware and software. The hardware is somewhat hidden so we could explain it at the functional level. Any software complexity will be hidden in an include file. Details of both could be provided to anyone who likes to know how things work.

Design Point 1B - ATmega ADC and Bipolar DAC Solution

This solution begins with a custom Analog Shield based on the Sparkfun Protoshield. This dual-sided PCB would have the DAC and ADC interface logic mounted on one side of the board, with a mini breadboard attached to the other. The Sparkfun Protoshield is illustrated in the Figure above which shows a nifty extension with 6-pins which in our design would provide for the analog input and output headers. The side with the breadboard would also have a socket allowing the DC/DC converter to be plugged in or provide easy access for jumper wires if the students want to use lab supplies (*not recommended*).

The circuit board would be made for the students to purchase with a reference design on it for the ADC, DAC, and DC-to-DC converter. The students would then wire their "plants"/integrators to their prototyping boards and jump over to the ADC/DAC header pins as needed.

The cost of the ADC interface components, DAC, and DC-to-DC converter for this solution is less than \$20.00.

- TDK CC1R5-0512DF-E DC/DC Converters 5v to +/- 12v. [Digi-key](#) has them in stock at \$9.85.
- Custom PCB Supports the following DAC Options
 - 8-pin DIP - 12-bit [AD7233](#) DAC with serial interface packaged in with an output that swings between +/- 5v with a +/- 12 to 15 v supply voltage. [Digikey](#) has over 300 in stock at \$14.36.
 - 16-lead TSSOP - Analog Devices [AD5530](#). This 12-bit DAC has a SPI serial interface comes as an with an output that swings between +/- 10v with a +/- 15 v supply voltage. [Digikey](#) has them in stock at \$9.21, along with [Avnet](#) at \$6.21.
- ATmega328P 12-bit ADC
 - MCP1525/1541 2.5V/4.096V Reference Supply, this is a TO-92 three-terminal device that provide a steady +2.5V or +4.095V voltage reference. This eliminates the op-amp buffer, voltage divider, and associated discrete components. Available from [Digikey](#) with over 4,000 in stock for \$0.92.
 - TBD Op-amp provides level shifting with associated discrete components.

Pluses

- Custom PCB means we control the design leading to a good ground and power plane, and no wiring errors for this part of the design.
- Allows the use of Surface Mounted or Through-hole parts.
- Simplified version of Spring '10 EE470 design
- Very low cost
- Software is done.

Minuses

- Requires custom PCB
- Difficult to teach hardware and software. The hardware is somewhat hidden so we could explain it at the functional level. Any software complexity will be hidden in an include file.

Details of both could be provided to anyone who likes to know how things work.

Design Point 1C +/- 10v Bipolar ADC and DAC SOIC Solution

This solution begins with a custom Analog Shield based on the Sparkfun Protoshield. This dual-sided PCB would have the DAC and ADC mounted on one side of the board, with a mini breadboard attached to the other. The reason I mention the Sparkfun Protoshield is illustrated in the Figure above which shows a nifty extension with 6-pins which in our design would provide for the analog input and output headers. The side with the breadboard would also have a socket allowing the DC/DC converter to be plugged in or provide easy access for jumper wires if the students want to use lab supplies (*not recommended*).

The circuit board would be made for the students to purchase with a reference design on it for the ADC, DAC, and DC-to-DC converter. With a custom PCB we could also look at alternative designs including parallel interface, single supply ADC and DAC with level shifters.

The students would then wire their "plants"/integrators to their prototyping boards and jump over to the ADC/DAC header pins as needed.

The cost of the ADC, DAC, and DC-to-DC converter for this solution is \$32.85.

- TDK CC1R5-0512DF-E DC/DC Converters 5v to +/- 15v w/ jumper. [Digi-key](#) has them in stock at \$9.85. *On custom PCB a socket could be provided allowing the student to purchase or use lab supplies.*
- DAC
 - Analog Devices [AD5530](#). This 12-bit DAC has a SPI serial interface comes as an 16-lead TSSOP with an output that swings between +/- 10v with a +/- 15 v supply voltage. [Digikey](#) has them in stock at \$9.21, along with [Avnet](#) at \$6.21.
 - Maxim/Dallas [MAX5322](#). This 12-bit ADC has a SPI serial interface comes as an 28-lead SSOP with an input swing between +/- 10v with a +5 to - 12 to 15 v supply voltage. [Digikey](#) has then in stock at \$12.79.
- ADC
 - Analog Devices [AD7366-5](#). This 12-bit ADC has a SPI serial interface comes as an 24-lead SSOP with an input swing between +/- 10v with a +5 digital and +/- 15v analog supply voltage (see Figure 5 in [pdf datasheet](#)). [Digikey](#) has the AD7366BRUZ-ND in stock at \$10.21

Pluses

Custom PCB means we control the design leading to a good ground and power plane, and no wiring errors for this part of the design.

Allows the use of Surface Mounted parts.

Minuses

Requires custom PCB be designed, fabricated, and assembled outside the University.

Design Point 2 +/- 10v Bipolar ADC and DAC DIP Solution

- LTC1605 - 16-Bit, 100ksps, Sampling ADC. This 16-bit ADC has a parallel interface and comes in a 28-pin DIP package. Not sure of source or pricing.
- LTC1821 - 16-Bit, Ultra Precise, Fast Settling VOUT DAC. This 16-bit DAC has a parallel interface and comes in a 28-pin DIP package. Not sure of source or pricing.
- Arduino Mega. The multiplicity of ports available on the MEGA would work nicely with the $2 \times 16 = 32$ I/O data lines. It would also simplify the coding avoiding the need for a 595.
- TDK CC1R5-0512DF-E DC/DC Converters

Plus

- Very simple electrical and software interface to teach.
- Without a custom PCB the students could still easily implement this interface.

Minuses

- Expensive to implement.
- Not very compact.
- With the Linear Technology in particular and perhaps with parallel load devices in general, I'm wondering if their (assumed) unpopularity will be difficult to find sufficient stock for short-term as well as long-term specification. That is, we need to specify devices that won't be phased out too soon and ideally has standardized footprints so that alternate devices can get dropped in. *It should be noted that the LT1605 is second sourced.*

Design Point 3 +/- 5v Bipolar ADC and DAC DIP Solution

This solution actually is pretty close to what I want for \$51.62 plus cost of Op-amps.

- TDK CC1R5-0512DF-E DC/DC Converters 5v to +/- 12v. [Digi-key](#) has them in stock at \$9.85.
- DAC is the [AD7233](#). This 12-bit DAC has a serial interface comes as an 8-pin DIP with an output that swings between +/- 5v with a +/- 12 to 15 v supply voltage. [Digikey](#) has over 300 in stock at \$14.36.
- ADC is the [MAX176](#). This 12-bit ADC has a serial interface comes as an 8-pin DIP with an input swing between +/- 5v with a +5 to - 12 to 15 v supply voltage. [Digikey](#) has over 100 in stock at \$27.41

Pluses

- Allows the use of DIPs which brings assembly back in-house.

Minuses

- Expensive DAC and ADC
- Input/Output swing limited to +/- 5v
- Expensive DC/DC converter suggested. The students will have the option to use the lab supplies - although this solution opens up mistakes by the students resulting in loss of the electronics and is therefore not recommended.

Design Point 4 Unipolar ADC and DAC 9 v Battery Solution

Two 9v batteries to supply +/- 9v plus 5v supplied by the USB connector for the digital logic. Next use a bipolar +/- 9v DAC and ADC. The hardware would then only be the 2 Op-Amps implementing the lead-lag circuit, plus a gain stage.

Pluses

- DC-to-DC converter replaced by low cost 9v batteries

Minuses

- Asymmetrical offset resulting from the use of two 9v batteries. Normally, an op-amp with a good PSRR would mitigate some of this offset, but when we have gains of 100 or more this could have been (will continue to be) a source of hard-to-track-down-and-troubleshoot error. *Solution would be to use two low cost \$0.71 [LM2931](#) low dropout (LDO) voltage regulators.*
- Requires custom PCB
- A lot of part to be inventoried and soldered
- Difficult to teach hardware (I will hide the software complexity in an include file)

Design Point 5 Unipolar ADC and DAC Spring '10 Solution

This is the elegant, compact, and low cost solution. We keep the ADC on the ATmega328P and simply place a level shifter on the output of the plant. I would not have problem with doing this if we designed a custom PCB solution where we could minimize noise and eliminate wiring errors. I am not comfortable leaving this up to the students on a breadboard. Until we get the capability to solder surface mount components, then I think we are limited to through-hole solutions. Consequently, on the output of the microcontroller (input to the plant) I would go with the AD7233 or use a MCP4921/level shifter solution. Now lets look at the pluses and minuses.

Pluses

- We could keep the design from the Spring '10 semester
- Very low cost
- Software is done

Minuses

- Requires custom PCB
- A lot of part to be inventoried and soldered

- Difficult to teach hardware (I will hide the software complexity in an include file)

Design Point 6 - Single Supply

This for me is the holy grail.

My single-supply design is based on a "Deboo" integrator, also known as a "Howland current source with a capacitive load" and is designed to work with single-supplies. Here is where you can read about it.

[Consider the "Deboo" Single-Supply Integrator](#)

When I first played around with this idea all I had was the inexpensive LM324 Op-Amp. This nice general purpose Op Amp was just not up to the task. For example, it has an input common-mode voltage range of $0\text{ V} + -1.5\text{ volts}$ (good but not good enough). I currently have in hand two parts which I think will both work. They have very low input bias currents of 1 pA and can go rail-to-rail on the input and output.

[Microchip MCP6002](#) - This part only costs \$0.36 and digi-key has over 3,500 in stock - so must be pretty popular. Supports rail-to-rail input and output swing, with a common mode input voltage range of $V_{SS}-0.3 \text{ --- } V_{DD}+0.3\text{ V}$

[Microchip MCP6022](#) - This part only costs \$1.42 and digi-key has over 500 in stock. This looks like the best part with a V_{os} of 250 uV along with a common-mode input range of $V_{SS}-0.3 \text{ --- } V_{DD}+0.3\text{ V}$.

Pluses

- We can use the ADC on-board the ATmega328P
- Everything fits in the Sparkfun Protoshield
- Looks really simple (although it is not)

Minuses

- Design is unproven
- Requirement to teach the Howland current source